HEAT AND MASS TRANSPORT IN NITROGEN ICE WITH APPLICATION TO PLUTO AND TRITON

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Abstract. Classical and "super" solid-state greenhouses have been suggested as mechanisms for the solar energy supply to Tritonian geyser-like plumes (Brown *et al.* 1990). In this work we evaluate solar and internal (owing to radioactive decay of U, Th and ^{40}K in Pluto's inferred core) heat sources and their corresponding mechanisms for predicted eruptive activity on Pluto. For the internal energy supply, a model of conductive-convective heat and mass transport on Triton (Duxbury and Brown 1997) is applied to Pluto's solid N_2 layer. Previous models of the solid-state convection for different celestial bodies considered only simple parametrized convect ion in H_2O ice. We have solved numerically the Navier-Stokes system in the Boussinesque approximation. Whether solid-state convection occurs in Pluto's and Triton's N_2 ice (and if it does, then its intensity) depends upon the solid nitrogen grain size and the thickness of the solid N_2 layer. We have computed the average N_2 grain size sufficient for the onset of convection as a function of the N_2 thickness in the case of perennial nitrogen deposits and corresponding Nabarro-Hering creep (volume diffusion). We have also performed computations for the case when convection is coupled with the "super" greenhouse in a seasonal N_2 layer. Convection in a seasonal N_2 layer on Triton and Pluto is plausible even without the solid-state greenhouse effect, because N_2 on these bodies is so close to its melting temperature of= 63.148 K (at zero pressure) that an upper stagnant layer does not form. Since $d_{grain} < 0.3\mu m$ for the fresh transparent N_2 deposits on Pluto (Duxbury *et al.* 1997), Coble creep (boundary diffusion) dominates in these deposits until grains grow to the critical size. We have generalized our conclusion for plausible convection in a seasonal layer for other bodies, on whose surfaces Van der Waals solids are near their melting temperatures (e.g. ,CH_4 on Titan). We have also proposed a method for estimating the thickness of Pluto's perennial solid N_2 layer during the future Pluto flyby mission (Pluto Express).

INTRODUCTION

Pluto is the smallest planet in the Solar System with an average radius between 1137 and 1206 km (Yoder 1995). A Pluto flyby mission is currently planned to be launched in March 2001, It will take 10 to 12 years to get to the planet at the outskirts of the Solar System. Having a highly elliptic orbit with an eccentricity of about 0.25 (Yoder

1995), Pluto can reach the farthest distance from the Sun of $\approx$ 50 AU, with an average distance being about 39.48 AU (Yoder 1995). Presently its distance from the Sun is slightly less ($\approx$ 29.6 AU) than of Neptune and its largest satellite Triton. What is known about the chemical composition of Pluto's surface comes mostly from the ground-based spectral observations led by Cruikshank (1976, 1980), with the recent important cent ribut ion by Owen *et al. (1993)*. They revealed that solid nitrogen is the dominant surface volatile (about 98 %). The derived abundance of solid methane is about 1.5 %, whereas on Triton it is only 0.05 % (Cruikshank *et al.* 1993).

The methane absorption band centers in Pluto's spectrum indicate that much of the CH_4 on Pluto is present as isolated patches of free CH_4, whereas on Triton it is more likely to form a solid solution with N_2. Some of the methane on Pluto is also diluted in N_2. The other minor surface volatile constituent on Pluto is solid carbon monoxide (about 0.5 %), which is more volatile than methane but less volatile than nitrogen at Pluto's temperatures. Carbon monoxide is probably present in a form of a solid solution with nitrogen. The second major difference bet *ween* the surfaces of Pluto and Triton is that, unlike on Triton, carbon dioxide ice was not detected on Pluto in the near-infrared spectral region.

Usually the absorption feature at 2.148 microns (on which the nitrogen detections on Pluto and Triton were based) is such a weak feature in the reflectance spectrum that a path in solid nitrogen has to be more than a meter in order for nitrogen to be detected at all. Thick nitrogen ice has many interesting implications because of its thermal insulating effect. Solid N_2 (as well as other solids: CH_4, CO, CO_2, whose molecules are bonded by weak Van der Waals forces) in the vicinity of 40 K has much lower thermal conductivity than the water ice. This means that temperatures are elevated at the base of a nitrogen layer,

By virtue of the latent heat of sublimation effects, the nitrogen surfaces on Pluto and Triton are nearly isothermal. Using ground-based spectroscopy, Tryka *et al.* (1994) estimated the surface temperature of Pluto's N_2 ice to be 40^{+2}_{-2} K, which is close to the current Triton's N_2 surface temperature of 38^{+1}_{-1} (Tryka *et al*,, 1993; Grundy *et al.*, 1993). The higher mean N_2 surface temperature of Pluto compared to Triton can be explained by the fact that Pluto has a lower overall albedo, thus presently absorbing more solar energy.

The current constraints on the surface pressure on Pluto are3t060pbar. The lower value was derived from stellar occultation measurements (Hubbard *et al.* 1990, Yelle and Lunine1989), but was later criticized by Stansberry *et* al. (1994), who considered that the occultation measurements did not probe alltheway down to the surface. The highest value in the pressure interval is obtained under the assumption that the surface and atmospheric nitrogen are in vapor pressure equilibrium.

TRITONIAN AND TERRESTRIAL GEYSERS

The above mentioned compositional and temperature analogies with Triton made it worthwhile calculating the value of an internal heat flow on Pluto in order to determine the applicability of our Triton's model (Duxbury and Brown 1997) for the subsurface convection in Pluto's solid nitrogen. The model was initially developed as an alternative to the solid-state greenhouse mechanism of energy supply to the Tritonian geyser-like plumes. The idea of internal energy as a source for Tritonian geysers was proposed long ago (e.g., Kargel and Strom 1990), but the corresponding numerical models, justifying it, were not presented.

The term "geyser" is commonly used for the liquid H_20 (and entrained CO_2, H_2S, etc., gases) eruptions on Earth. It may be more correct to call the Tritonian eruptions fumaroles, since they were nitrogen GAS with dust rising to about 8 km. The mechanism for volcanos on Earth is thought to be the same as for geysers with the only difference being in erupting material. Terrestrial geysers are mostly of the boiling type with H_20 and CO_2 as the primary erupting material, e.g. geysers in Kamchatka and Old Faithful in Yellowstone Park. Condensing geyser volcanism (which is the main type on Triton) of H_2O is rare on Earth.

Remarkably, solid N_2 and silicate rocks behave similarly (and opposite to that of H_20 ice) with respect to pressure induced melting: their melting temperatures drop if the pressure is reduced. Hence the formation of a deep crack (vent) on Earth may bring rock's melting temperature down to the rock's ambient temperature. Therefore, a mechanism of terrestrial volcanic eruptions without magma chambers is possible (Valerii Drozdov, Kamchatka Volcanology Institute, personal communications). For N_2 ice the 63.148 K is the melting temperature at zero pressure and thus is the minimum melting temperature. At the base ofal-km nitrogen layer on Pluto and Triton, thepressure is only about 7.9 bar, which does not influence the melting temperature noticeably.

ESTIMATES FOR PLUTO'S INTERNAL HEAT FLOW

Following McKinnon (1989) and Stern (1989), we deem Pluto to be completely differentiated, We adopt thesame model of Pluto's internal structure as was suggested for Triton by Smith *et* al. (1989). The model implies a rocky core, overlaid by a water-ice mantle and a surface veneer of volatile (mostly nitrogen) ices. The bulk density estimate for Pluto is very close to Triton's average bulk density of 2.054 g/cm^3 (Smith *et al.* 1989). But even if the densities of these two bodies were equal, Pluto's smaller size may preclude it from having a surface value of the internal heat flow as high as that on Triton, since surface heat flow is proportional to a body's radius, Hence, separate calculations are needed for Pluto.

Using the conclusions of Stansberry *et al.* (1994), we assume that a strong thermal inversion layer prevented the underlying atmosphere from being sensed by the stellar occult ation. Thus, we adopt Pluto's radius of 1150 km, as was derived by Tholen and Buie (1990) from mutual events, rather than 1195 km calculated from the stellar occultation data (Minis *et al.* 1993). We took the value of Pluto's mass from Young *et al.* (1994) astrometrically determined range of $119.08 * 10^{20} - 128.83 * 10^{20}$ kg. The main uncertainty stems from the determination of Charon's orbital semimajor axis. For the average mass value from this interval, $\rho_{mean} = 1.95\ g/cm^3$. This is consistent with $\rho_{mean} = 2.00\ g/cm^3$, derived by Foust *et* al. (1995).

The next formula relates the mass of the rocky core of a body to the body's mean bulk density:

$$\frac{M_{core}}{M_{body}} = \frac{1 - (\rho_{water\ ice} / \rho_{mean})}{1 - (\rho_{water\ ice} / \rho_{core})},$$

where $\rho_{rock} = 3\ g/cm^3$ is the average rock bulk density and $\rho_{water ice} = 1 g/cm^3$ is the water ice bulk density, Thus a rocky core comprises as much as $\approx 73\%$ of the total Pluto's mass. This estimate is consistent with the historical considerations of McKinnon and

Brackett (1994). Using a collisional formation model with water ice jetting and subsequent ice loss for Pluto, they justified Pluto's mass ratio: 75% of a rocky core versus 25910 of ice.

We have calculated the range of Pluto's total radiogenic heat flow to be 4.93* 10^{10} – $8.32 * 10^{10}$ W. Themaximum corresponds tothespecific (per unit mass) radiogenic heat production of 9.2 * 10^{-12} W/kg measured for the lunar samples, and the minimum corresponds to the specific heat production of 5.45 * $10^{-1}2$ W/kg, measured for chondritic meteorites (Schubert *et al.* 1986). We have calculated the final range of Pluto's internal heat flow at the surface as 2.97* 10^{-3}– 5.00 * $10^{-3}W/m^2$. Since the total temperature difference across a layer is the same for pure conduction as that for conduction with convection, we equate the calculated heat flow and$\lambda \frac{\partial T}{\partial y}$.The thermal conductivity λ of solid N_2 in the temperature range possible in Pluto's N_2 layer is about $0.2\,W/mK$. Hence, the temperature difference across the N_2 layer is 14,85-25 K, which is only slightly lower than the range obtained for Triton. A high temperature gradient in nitrogen ice on these bodies is due to good thermal insulating property of solid nitrogen. The low absolute value of the upper boundary temperature is influencing the convective model only indirectly through the strongly temperature dependent viscosity of solid nitrogen. In this dependence the proximity of the nitrogen temperature to the N_2 melting temperature is important.

SOLID NITROGEN EQUATORIAL BAND OR POLAR CAPS ON PLUTO?

According to Ward's (1974) calculations, the critical obliquity, above which the minimum of the mean annual insolation per unit area is at the equator rather than at the poles, is about 54 deg. Currently there are a few objects in the Solar System satisfying this condition: Uranus with the obliquity of 97.86 deg (and its satellites) and Pluto with the obliquity of about 122 deg. Probably Mars' obliquity at certain times could have overcome the critical value, since it was shown that on time scales greater than 107 Earth years Martian obliquity behaves chaotically reaching as high as 60 deg (e.g. Jakosky *et al.* 1995). Spencer *et al.* (1996) calculated that the current annual mean insolation at the Pluto equator is about 230 erg/cm^2s, which is slightly less than about 260 erg/cm^2s at the poles.

As it was shown by Brown and Kirk (1994), PERMANENT solid N_2 deposits are stable in the regions of long-term minima in the ABSORBED solar flux. Therefore, a perennial solid nitrogen equatorial "belt" may be expected for Pluto. However, strong surface albedo inhomogeneities were revealed by mutual event observations (Buie *et al.* 1992; Young and Binzel 1993) and by more recent images obtained by Stern *et al.* 1997 in June 1994 using the Faint Object Camera on the Hubble Space Telescope (HST). Owing to these surface albedo inhomogeneities, a perennial nitrogen deposit can be STABLE ANYWHERE on Pluto. There is a discrepancy between the HST images and the mutual event observations (Buie *et al.* 1992). According to the HST images, the brightest spot is on the equator, whereas the mutual events show it on the south cap. A definitive answer to this disagreement will likely have to be preceded by spacecraft exploration. Two spacecraft are currently planned to be launched to Pluto in March 2001.

In order to determine Pluto's regions with the minimum ABSORBED insolation, albedos at different locations have to be known with much higher precision than they are known today. Especially, because currently the incoming solar flux at Pluto's POLES is ONLY SLIGHTLY GREATER than that at the equator (Spencer *et al.* 1996), and a darker equator (higher value of (l-A)) may cause the ABSORBED insolation to be higher there. Nevertheless, the application of our model depends on the thickness of these deposits but not on their locations.

"Old" ice on Pluto may look darker than on Triton because Pluto has more solid CH_4. This reconciles the existence of a bright permanent polar capon Triton with the possibility of the existence of dark PERENNIAL contaminated nitrogen ice on Pluto. Photon and charge particle bombardment of CH_4 inclusions in N_2 ice produce dark organics, making "old" contaminated nitrogen ice look dark. In this case, ONLY the conductive-convective mechanism of energy supply to the plausible eruptions is feasible.

If the rate of nitrogen condensation is low enough, as appears to be the present case for Triton and Pluto, N_2 condenses as a transparent layer (laboratory experiments and calculations by Duxbury *et* al. 1997). The Pluto albedo maps derived by Buie *et* al. (1992), Young and Binzel (1993) from mutual events, show that the planet has an extensive bright southern polar cap and a small or non-existent northern polar cap. (Here we use the angular momentum vector for the definition of Pluto's North Pole). Therefore, it is conventional to speak about N_2 polar caps on Pluto.

REDISTRIBUTION OF THE INTERNAL HEAT FLOW OWING TO CONVECTION IN N_2 ICE

Accordingly, our modeling for Triton maybe applicable to convection in Pluto's upper frozen nitrogen layer, provided this layer is thick enough and the solid nitrogen grain size is sufficiently small. Therefore we may expect to observe the nitrogen geyser-like plumes on Pluto as well. Methane geysers are unlikely to operate on Pluto because the CH_4 equilibrium vapor pressure of 15 μ bar requires a temperature of about 53 K, and the CH_4 equilibrium vapor pressure of 3 μ bar (the lower estimate for Pluto's lower atmospheric pressure) requires a temperature of about 50 K (Brown and Ziegler 1979). This is much higher than the surface temperature of Pluto's volatile ice of about 40 K (Tryka *et al.* 1994). Our modeling (Duxbury and Brown 1997) was performed for the case when the basal temperature (63 K) was lower than the nitrogen melting temperature (63.148 K at zero pressure and increases with pressure, see Scott 1976).

As in any problem with a strongly temperature dependent viscosity, a question arises about the temperature at which to evaluate the parameters (especially viscosity) constituting the Rayleigh number. This is equivalent to the problem of the formation of an icy lithosphere on top of convecting N_2 layers, whose viscosity contrast is large. The viscosity contrast for Pluto's perennial N_2 ice is caused by the temperature difference of about 23 K between the lower and the upper boundary temperatures. All techniques to take into account this conducting overlayer in a SINGLE REPRESENTATIVE temperature (at which thermophysical characteristics of a convecting layer are evaluated) were developed either for terrestrial planets or for the H_2O-ice satellites (mostly Galilean and Saturnian satellites). The absence of convection in the H_2O-ice upper layer is substantiated by observations (McKinnon *et* al. 1996) and the fact that water ice on Pluto and Triton is too far from its melting temperature. Here we argue that, though these considerations may be applicable to the water-ice mantle convection on Pluto and Triton (McKinnon *et* al. 1996), they are not applicable to convection of nitrogen ice on these bodies.

First, the peculiarity of N_2 ice is that it is much closer to its melting point on Pluto and Triton than H_2O ice on most bodies in the Solar System. Actually, N_2 on Pluto and Triton is in the same vicinity of its melting point as water ice in terrestrial glaciers. The base of the lithosphere is defined by the MINIMUM temperature T_l sufficient for creep to occur on a geological time scale. Creep in solids is caused by self-diffusion, which is a thermally activated process. It is a common phenomena in solids, at least in the vicinity of their melting points (see experiments by Esteve and Sullivan (1981) with pure and cent aminated lV$_2$). The approach by Ellsworth and Shubert (1983) for the mid-sized satellites of Saturn uses the formula $T_l = 0.6 * T_{melting}$. This formula is based on the creep data for metals that show the occurrence of solid-state creep at temperatures $\geq$ than $0.6 * T_{melting}$. The application of this approach gives the temperature of= 37.89 K at the base of the assumed Pluto's N_2-ice lithosphere. This is even less than the lower limit of the spectrally measured temperature of 40^{+2}_{-2} K at Pluto's surface. Hence, we must take $T_l = T_{up}$. Though laboratory experiments gave $0.6* T_{melt}$ as the MINIMUM temperature SUFFICIENT for creep to occur during laboratory times, on GEOLOGICAL time scales creep may occur at lower temperatures. This additionally substantiates our concept that the very UPPER N_2 layer is convecting on Pluto and Triton. Therefore, we evaluate the thermophysical coefficients in Pluto's N_2 layer at the average of the upper and lower boundary temperatures, as we did for Triton (Duxbury and Brown 1997).

Secondly, from a theoretical standpoint, the bonds between water-ice molecules in a crystalline lattice are strong hydrogen bonds, (with the two kinds of H-bonds being randomly distributed, Jichen and Ross 1993) whereas in N_2 ice intermolecular bonds are weaker (electrical) Van der Waals bonds.

Thirdly, there are no sufficiently resolved observations of Pluto's surface to make a conclusion about the involvement of the N_2 surface layer in convection. For Triton's surface there are only Voyager 2 observations in August 1989 (its surface is not resolved from the Earth), thus it is impossible to compare the state of the surface at two different epochs. Moreover, there is some morphological evidence from the Voyager 2 images for diapirism on Triton (cantaloupe terrain, Schenk and Jackson 1993). Presumably, this crustal overturn is driven by compositional layering of Triton's crust. The authors have noted that thermal convection may also be important as the driving mechanism.

Using the dimensionless formulation corresponding to the formulation from Duxbury and Brown (1997), we have computed that the closest approach to the surface of the $T_{up} + 1\ K$ isotherm is about 16 m for $Ra/Ra_{critical}$ = 5, where $Ra_{critical}$ = 1100.65 (Chandrasekhar 1981). This number is the minimum Rayleigh number required for the onset of convection for the upper stress-free and lower rigid boundary conditions. The minimum is taken with respect to all horizontal wavenumbers. The parameters used in our computations are summarized in Table 1. For nitrogen ice the Prandtl number is essentially infinite (see Table 1 and cf. the Pr number for liquid nitrogen). This significantly simplifies the hydrodynamic part of the problem in consideration by reducing the Navier-Stokes system to the Stokes system.

Even a small decrease in the average grain size gives a significant rise to the ratio $Ra/Ra_{critical}$. Therefore, we investigated Pluto-and-Triton-like conditions, which will give the needed $Ra/Ra_{critical}$. The results for thick perennial N_2 layers are shown in Fig. 1. Plots in Fig. 1 present the thickness of a perennial nitrogen layer versus nitrogen grain diameter. These layers are thick enough to start thermal convection (the curves marked by filled circles) and to achieve $Ra = 5 * Ra_{critical}$ in thick N_2 layers (the curves marked by open triangles). A pure conductive thermal gradient of 0.0225 K/m is assumed (no solid-state greenhouse effect). For the grain diameters corresponding to 800 - 1000-m-thick layers on these curves and for Triton's - Pluto's temperatures, Nabarro-Herring volume diffusion dominates (Duxbury and Brown 1997). For the higher pair of curves the volume self-diffusion coefficient of nitrogen ice is assumed to be equal to the average estimate from the measurements of Esteve and Sullivan (1981), For the lower pair the self-diffusion coefficient is taken at the upper limit from the same experimental measurements.

The nitrogen grain size is an important parameter. If we measure the rate of nitrogen grain growth in a laboratory under the Pluto-like conditions, in order to make a conclusion about the grain size at the end of Pluto's winter season, we need to know the original size. The dynamic viscosity is proportional to the 2nd power (for the Nabarro-Herring volume diffusion creep) or to the 3rd power (for the Coble boundary diffusion creep) of the grain diameter.

CONVECTION IN A SEASONAL NITROGEN LAYER?

Earlier we examined the conditions sufficient for the onset of convection in a thick perennial N_2 ice. Itisinteresting tonotethat convection mayoccur evenin aSEASONAL N_2 ice. Though its thickness is much smaller than that of perennial deposits, the sufficient condition $Ra > Ra_{critical}$ may still be satisfied because of the small original grain diameter and not enough time lapsed for grains to anneal into larger grains. As we have shown in Duxbury *et al.* (1997), the initial grain size on Pluto (and moreover on Triton) is $< 0.3\mu m$. This estimate, can be improved by using the emissivity $\epsilon = 0.8$ for the β phase of nitrogen (Stansberry *et al.* 1996) instead of the nominal value $\epsilon = 1$ originally used by Eluszkiewicz (1991). Additionally, some evidence for small particles on Triton is provided by the scattering properties of discrete clouds, with particle sizes 0.2 -0.4 μm in radius (Hillier and Veverka 1994).

At SMALL grain sizes under consideration and Triton's temperatures the Coble (boundary) diffusion creep dominates (a letter to N. S. Duxbury dated March 31, 1995). Thus, we have used in our calculations for Pluto's SEASONAL N_2 layers the dynamic viscosity proportional to the 3rd power of the grain size instead of the 2nd power as for volume diffusion used for PERENNIAL layers (Nabarro-Herring creep). We have calculated the nitrogen dynamic viscosity using the grain-boundary diffusion coefficient (Goodman *et al.* 1981):

$$D_b(T) = D_{0b} \times exp(-E_b/(RT)), \quad m^2/s,$$

where the preexponential factor $D_{0b} = D_{0v} = 1.6 \times 10^{-7}\, m^2/s$ (Ashby and Verrall 1978, Eluszkiewicz 1991), $E_b = (2/3) \times E_v = 5.7 \times 10^3$ J/mol is the activation energy for the boundary diffusion (Eluszkiewicz 1991, pp. 19219- 19220), the universal gas constant R=8.3145 J/(mol K) and T is the temperature.

We used this coefficient in the dynamic viscosity formula for polycrystalline solids with Coble diffusion creep (Raj and Ashby 1971, p. 1121):

$$\eta_b(T_{average}) = \frac{d_g^3 k_B T_{average}}{141 \times \delta \times D_b(T_{average}) \times \Omega}, \quad Pa \bullet s,$$

where $\Omega = 4.7 \times 10^{-29}/m^3$ is the N_2 molecular volume, $\delta = 2\Omega^{1/3} \approx 7.2 \times 10^{10}$ m is the width of a nitrogen grain boundary (Eluszkiewicz 1991), k_B = 1.381 x 10^{-23} J/K is the Boltzmann constant, d_g is the grain diameter (assuming spherical grains), and $T_{average}$ is an average of the upper and lower boundaries temperature,

In our program we calculated $T_{average}$ as a function of the N_2 layer's thickness, of a pure conductive gradient and of the upper boundary temperature.

In our computations we have used the temperature dependence of N_2 thermophysical characteristics from Scot t (1976). We have used a seventh-order polynomial for the approximation of density, second-order polynomials for the heat resistivity (the inverse of the heat conductivity), and third and second-order polynomials to approximate the N_α and the N_β heat capacity, respectively. Note that for a fixed $\nabla T_{conductive}$ the average of the upper and lower boundary temperature (at which coefficients are taken in the Ra number) is a function of depth.

The maximum thickness of a seasonal N_2 layer on Triton is about 10 m. On Pluto it can be even more, if we extrapolate the current condensation rate on these bodies over their winter seasons. Results of our computations for seasonal N_2 layers are shown in Fig. 2. They demonstrate N_2 grain diameters sufficiently small for thermal convection to start versus the thickness of a seasonal N_2 layer (the curve marked by filled circles). The second curve, marked by open triangles, shows nitrogen grain diameters sufficiently small for the Rayleigh number to be 5 times that of the critical for the free-rigid boundary case ($Ra_{critical}$ = 1100.65). Solely radiogenic heating is assumed. The average internal heat flow of 4.6 * $10^{-3} W/m^2$ is used for Pluto. This corresponds to the average thermal gradient of 0.023 K/m. If N_2 ice on Pluto and Triton would not be so close to the melting temperature, a stagnant layer would form on top, possibly preventing seasonal transient convection.

COUPLING THE SOLID-STATE GREENHOUSE EFFECT AND CONVECTION IN N_2 ICE

The thickness of the N_2 layer sufficient for the onset of convection in a seasonal layer is much smaller if we calculate the temperature difference between the upper and the lower boundaries considering the solid-state greenhouse effect. Since it is likely that nitrogen initially forms a transparent layer (experiments by Duxbury *et al.* 1997) on top of a dark substrate, the "super" solid-state greenhouse effect can occur (Brown *et al*, 1990). Note that the solid-state greenhouse effect does not require continuous sunlight and thus can occur in Pluto's southern hemisphere, where the seasonal N_2 layer is currently growing. Pluto's subsolar point has crossed the equator in 1986 moving north at a rate of about 2 deg/earth year, hence the regions from the south pole down to about 70 S are in continuous darkness. (We again use the angular momentum vector to define Pluto's North Pole). The condition for the daily averaged insolation, sufficient for the greenhouse effect to work, can be found in the Appendix of the article by Matson and Brown (1989).

In our computations described below we have coupled the solid-state greenhouse effect and convection. Results in Fig. 3 illustrate the grain sizes sufficiently small for convection to start in a seasonal layer with the solid-state greenhouse effect (the curve marked by filled circles). The curve marked by open triangles shows N_2 grain diameters sufficiently small to obtain $Ra = 5 * Ra_{critical}$. The "super" solid-state greenhouse effect is assumed with a dark underlayer having an albedo of 5%, thus giving the conductive gradient of 4 K/m (Brown *et al.* 1990). This is about 174 times more than the average thermal gradient of 0.023 K/m calculated using only radiogenic heating (Fig. 2).

The plots in Fig. 4 represent an intermediate case of nitrogen grain diameters sufficiently small for thermal convection to start in a seasonal layer with the solid-state greenhouse effect (the curve marked by filled circles). The "super" solid-state greenhouse effect is assumed with an intermediate value of 1 K/m for the conductive gradient (the dark underlayer having an albedo > 5%). The curve with open triangles shows N_2 grain diameters sufficient to obtain $Ra = 5 * Ra_{critical}$.

METHODS TO ESTIMATE N_2 GRAIN DIAMETER AND N_2 ICE THICKNESS

Solid-state convection occurs on Pluto if the solid nitrogen average grain size is small enough and the N_2 ice layer is sufficiently thick. The grain diameter in PERENNIAL nitrogen ice can be assessed using the semiquantitative Zener theory (Kirk, personal communications; A letter by R. Kirk to N. S. Duxbury dated 31 March 1995; Duxbury and Brown 1997). Dust grains are inhibitors for the growth of the ice grains, though, as experiments with metals showed, the cessation of the grain growth may occur even in pure substance (Smith 1948). The dust flux on Triton was estimated by Pollack *et al.* *(1990)* from the optical atmospheric properties measured during the Voyager 2 flyby in August 1989. Unfortunately, this value is not known for Pluto, since the planet has not been visited by a spacecraft. The rate of cometary impacts was estimated for the Pluto- Charon binary by Weissmann and Stern (1994). Due to a higher than on Triton flux of comets from the Kuiper belt and from the inner Oort cloud, the dust, brought by these impactors, is probably more abundant on Pluto. Hence, the estimate for the maximum grain size of $\approx$ 1 cm, which we have obtained for Triton (Duxbury and Brown 1997) can be applied and even reduced for Pluto. This makes the solid-state subsurface convection in perennial N_2 deposits more probable on Pluto than on Triton, assuming the same thickness of the perennial N_2 ice.

The other parameter important for calculating the Rayleigh number is the total thickness of the nitrogen layer. In this connection we propose here a new method of determining this thickness during the future Pluto flyby mission. We have dubbed it the "crater" method. By analizing the state of relaxation of the ejects we will be able to determine whether the ejected material is near its melting point. At Pluto's surface temperature of about 40 K, N_2 ice will flow readily. If a crater's depth is great enough to extract H_2O " ice, this ice (being very far from its melting temperature) forms rampart craters. It will be possible to determine a crater's depth using stereo images. (The resolution of the proposed Pluto flyby camera is planned to be better than Voyager's best resolution of 1 km/pixel). Then by comparing the relaxation of the ejects for different craters, and thus for different depths, we can estimate the depth of the perennial N_2 layer at different locations. The second method of determining the depth of a crater is photoclinometry, but its application on Pluto will be hampered by large surface albedo contrasts. Ground-based infrared spectroscopic observations also allow to estimate the ratio of $^{15}N_2$ to the regular isotope $^{14}N_2$ (Brown *et* al. 1997). If this ratio is high, then a significant portion of the regular nitrogen isotope has escaped and it is likely that the perennial nitrogen ice on Pluto is relatively thin.

DISCUSSION: NITROGEN GEYSERS ON PLUTO?

It was estimated theoretically (under the assumption that all dark streaks on the surface of Triton's south polar cap are extinct plumes) that the lifetime of Tritonian geyser-. like plumes is 1-5 Earth years (Smith *et al.* 1989). This is consistent with our conclusion that the plumes can form in a SEASONAL N_2 layer. The initially condensed grains grow through the formation of a neck between two grains (pressureless sistering). The process is driven by the surface tension and the differences in grain curvatures. When the average grain size exceeds the critical value, which is coupled with the thickness of the growing layer via the Rayleigh number, convection ceases.

The probability of internally driven geysers on Pluto is somewhat lower than that on Triton due to Pluto's smaller size, which results in a slightly smaller internal heat flow at the surface (this heat flow is proportional to the body's radius). Secondly, smaller gravity acceleration gives a smaller Ra (the Rayleigh number is proportional to gravity). Thirdly, the N_2 escape rate on Pluto was estimated to be higher than that on Triton due to the heating of Pluto's upper atmosphere (Trafton *et al.* 1996). This possibly results in a smaller nitrogen amount currently available. Although the extrapolation of the presently high escape rate over the age of the Solar System may not be possible, since then there would be no volatiles currently on Pluto. Ground-based observations by Owen *et al.* (1993) showed the presence of nitrogen, met bane and carbon monoxide on Pluto's surface.

Continuous sunlight is not needed for the solid-state greenhouse effect. The formula for the temperature difference between the subsurface and the surface value includes the insolation averaged over the diurnal cycle (Mat son and Brown 1989). Physically, it means that the solar energy acquired during the day may be enough to drive the plumes at night. Whether the solar heating is enough is determined by the solar constant of a body and by the season. Nevertheless, in at least two cases, only the internal heat can drive the plumes. These are the existence of the plumes during a continuous night and the opacity of the surface layer. The N_2 layer is probably darker on Pluto than on Triton, due to the higher abundance of CH_4 and its photochemical darkening. If plumes are detected on Pluto, they are more likely to be internally powered, because the solar constant at 39,48 AU (Pluto's mean dist ante from the Sun) is less than that at 30 AU(Triton's dist ante from the Sun).

An observational test for the solid-state greenhouse involves the moderation of the surface temperatures and a delay in the maximum diurnal surface temperature (maximum is reached later than at the local noon). An observational test for the internal origin of the plumes includes a detection of a geyser in a region of continuous darkness. We recommend to conduct thermal IR observations of Pluto's south polar region, which will be in the polar night down to about 40 S in 2011 (time planned for the Pluto flyby), Another observational clue for convection involves morphological evidence, e.g., cantaloupe terrain and volcanic depressions on Triton (Kargel and Strom 1990). Recent spectroscopic studies of $^{15}N_2/^{14}N_2$ put additional observational constraints on N_2 thickness on Pluto and Triton (Brown *et al.* 1997). An additional support "for the locally higher internal heat flow is rendered by the three volcanic landforms in Triton's equatorial region detected in the Voyager 2 images by the two groups of investigators (Kirk and Brown 1991; Helfenstein et al. 1991, 1992).

FUTURE WORK

Since convection in a seasonal layer is possible, it is interesting to understand, how high will a "warm" solid N_2 parcel rise from the bottom of a seasonal layer during one winter season. More realistic (and thus more complicated) problem is, how high it rises before the average grain size becomes large enough for convection to cease and/or before the seasonal layer sublimates to the thickness less than the critical (whatever comes first). Convective velocity could be estimated via the Ra number using the work by McKenzie *et al.* (1974, p. 494) and an estimate for the rate of the N_2 grain growth can be taken from Eluszkiewicz (1991). In our case the convective velocity will be diminishing gradually since the Ra number will be attenuating with the increase in the average grain size.

The possibility of convection in a thin N_2 layer under Pluto-like conditions can be tested in a laboratory. Since the expected convective velocities for small supercritical Rayleigh numbers are on the order of 1 mm/earth year (Duxbury and Brown 1997), it will be reasonable to put a weight on top of the N_2 layer. This will increase the gravity acceleration, and hence the Ra number and the convective velocity. With a solid weight on top, the upper stress-free boundary condition changes to the rigid one, thus changing the critical Ra number from 1100.65 to 1707.762 (for symmetrical rigid boundary conditions). A liquid layer on top of solid nitrogen will allow to avoid the problem.

SUMMARY

In our previous work (Duxbury *et al.* 1997) we estimated the initial grain size at which N_2 currently condenses on Pluto and Triton to be < 0.3pm. The estimate can be *some*-what improved using the emissivit y of 0.8 (Stansberry *et* al. 1996) for the hexagonal N_2. Additional evidence for small particles on Triton is provided by the scattering properties of discrete clouds, with particle sizes 0.2- 0.4 μm in radius (Hillier and Veverka 1994). Theoretically N_2 ice at Pluto's temperatures can begin to convect having an arbitrary small thickness, if N_2 crystals are small enough, i.e.: $Ra \propto d^3/d^3_{grain} \geq const(Ra_{critical})$. In the last condition the 3rd power of the grain diameter was used instead of the 2nd (Nabarro-Herring diffusion), since, as we have shown above, in a freshly condensed nitrogen Coble diffusion creep dominates Nabarro-Herring diffusion. This allows for larger grains in order to obtain the same Rayleigh number. Because the upper boundary temperature is greater than 0.6 * $T_{melting}$, the stagnant layer is unlikely to form on top of convecting N_2 ice on Pluto and Triton, making a transient thermal convection possible in a seasonal layer.

A vent (provided by the crystalline phase transition) does not have to be directly above an upwelling plume because there can be a lateral N_2 vapor transport. It occurs in horizontal fissures due to the pressure difference, since P(vent) is slightly lower than that away from the vent due to the lower temperature at the vent. The T(vent) is lower because sublimation at the vent absorbs the latent heat.

In conclusion, we would like to underscore that solid nitrogen is a unique material in the sense that on Pluto and Triton it probably convects all the way up to the surface without forming an upper stagnant layer because it is a weakly bonded solid near its melting temperature. This behavior can be generalized for other Van-der-Waals solids ($C0_2$, NH_3, CH_4, CO) near their melting points. For example, our conclusions can be extended for solid methane on the Saturnian satellite Titan. The melting temperature of methane is about 90.67 K, which is very close to the estimated average surface temperature on Titan. Creep in solid methane occurs at temperatures $\geq 54.402\ K$ = 0.6* $T_{melting\ methane}$. This temperature would be considered the temperature at the base of the upper stagnant layer, if any.

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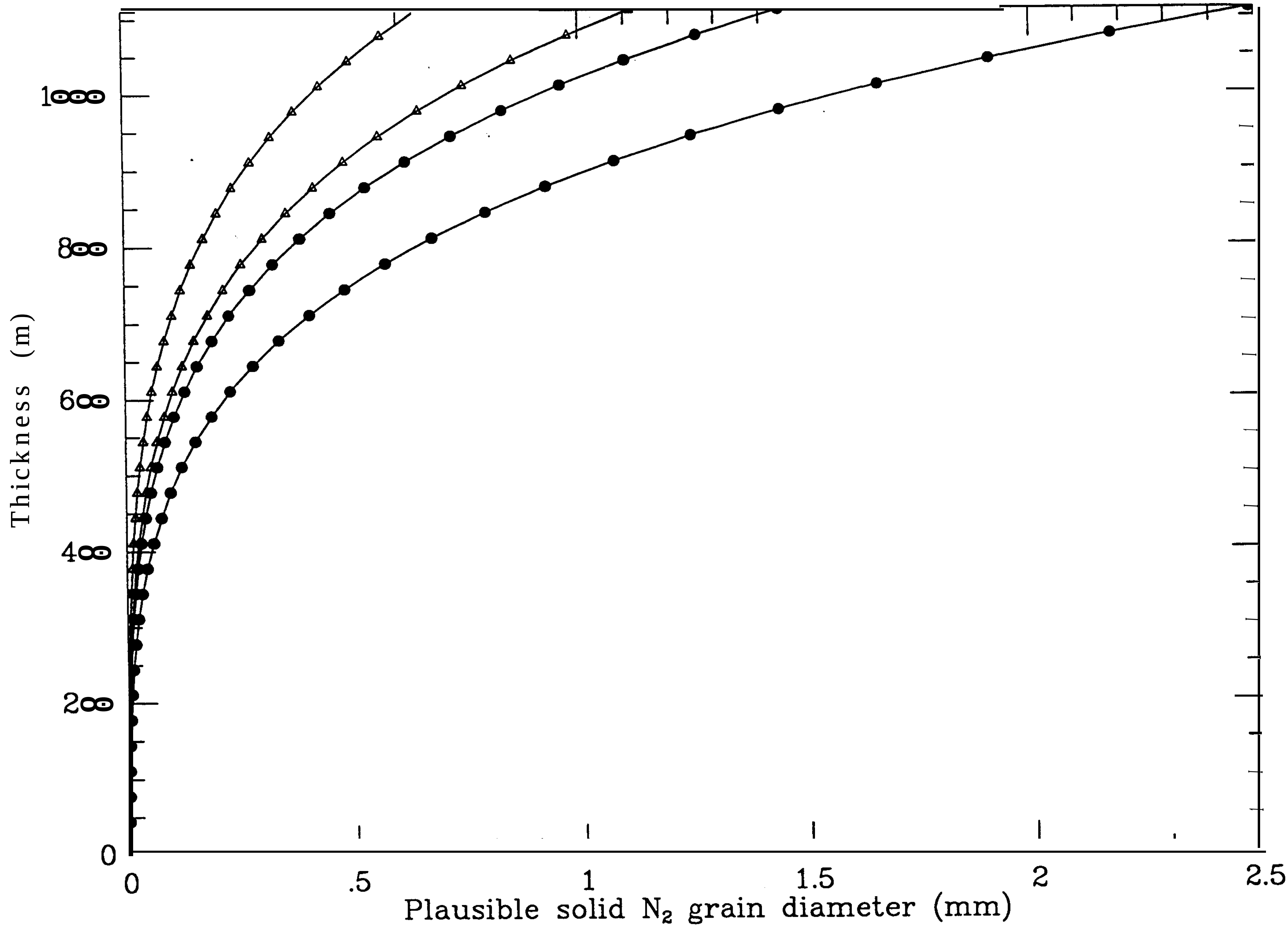
FIGURE CAPTIONS

Fig. 1. Thickness of perennial nitrogen layers versus nitrogen grain diameter. These layers are thick enough to start thermal convection (Ra = $Ra_{critical}$ for the curves marked by filled circles) and to achieve $Ra = 5 * Ra_{critical}$ in thick N_2 layers (the curves marked by open triangles). For the free-rigid boundary case $Ra_{critical}$ = 1100.65 A pure conductive thermal gradient of 0.0225 K/m is assumed (no solid- state greenhouse effect). For the grain diameters corresponding to 800- 1000-m-thick layers on these curves and for Pluto's temperatures, Nabarro-Herring volume diffusion dominates (Duxbury and Brown 1997). For the higher pair of curves the volume self-diffusion coefficient of nitrogen ice is assumed to be equal to the average estimate from the measurements of Esteve and Sullivan (1981). For the lower pair the self-diffusion coefficient is taken at the upper limit from the same experiment al measurements.

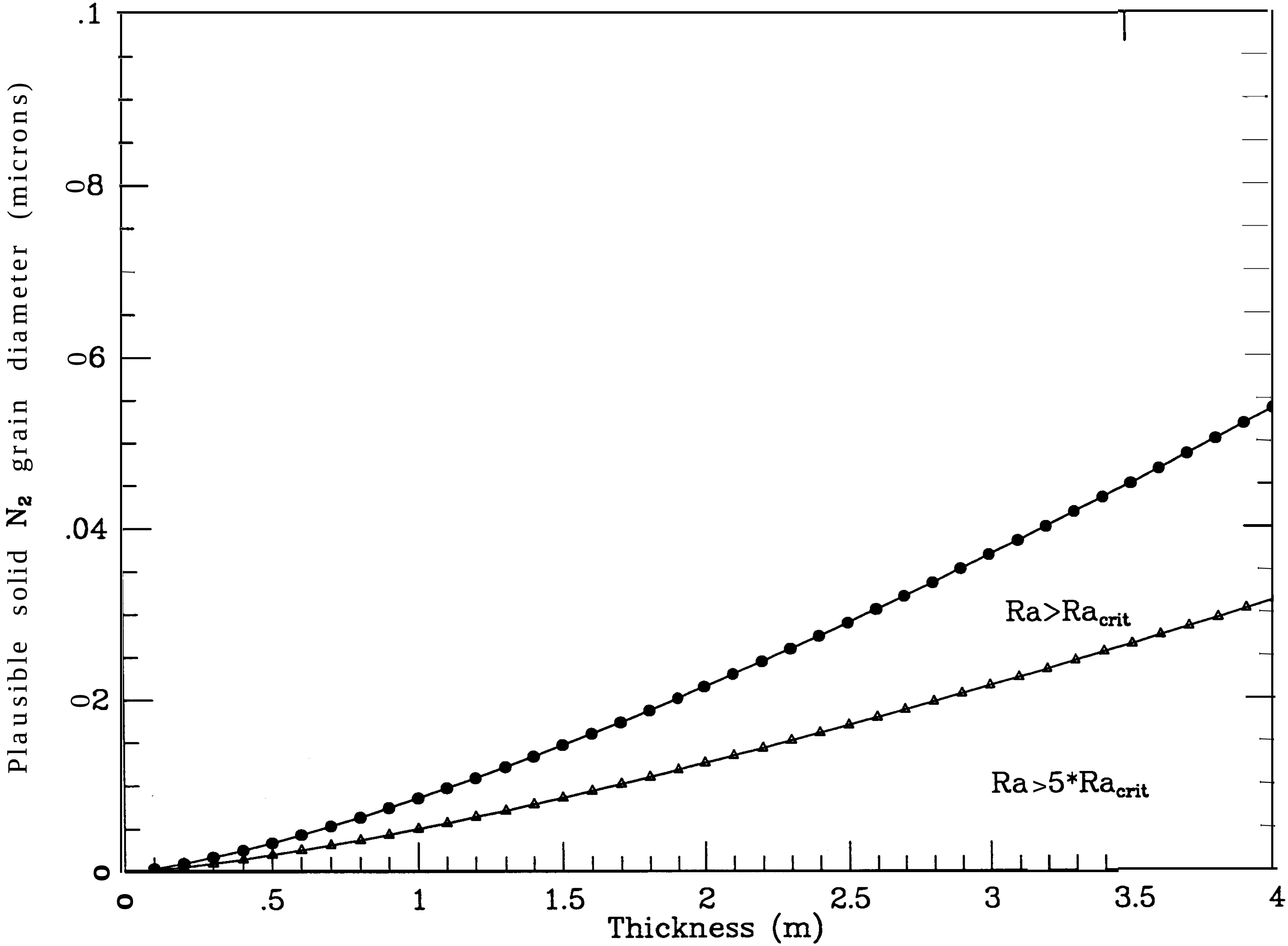
Fig. 2. Nitrogen grain diameters, assuming spherical grains, sufficiently small for thermal convection to start ($Ra = Ra_{critical} = 1100.65$) as a function of the thickness of a seasonal N_2 layer (the curve marked by filled circles). The second curve, marked by open triangles, shows nitrogen grain diameters sufficiently small for the Rayleigh number to be 5 times that of the critical. Solely radiogenic heating is assumed. The average internal heat flow of $4.6 * 10^{-3} W/m^2$ is used for Pluto. This corresponds to an average thermal gradient of 0.023 K/m.

Fig. 3. N_2 grain diameters sufficiently small for thermal convection to start in a seasonal layer with the solid-state greenhouse effect (the curve marked by filled circles). The curve marked by open triangles shows N_2 grain diameters sufficient to obtain $Ra = 5 * Ra_{critical}$. The "super" solid-state greenhouse effect is assumed with a dark underlayer having an albedo of 5%, thus giving the conductive gradient of 4 K/m. This is about 174 times more than the average thermal gradient of 0.023 K/m calculated using only radiogenic heating (Fig. 2). At those small grain sizes and Pluto's temperatures the Coble diffusion creep is dominating. Thus, we used in our calculations the dynamic viscosity proportional to the 3rd power of the grain size instead of the 2nd power as for the volume diffusion (Nabarro-Herring creep).

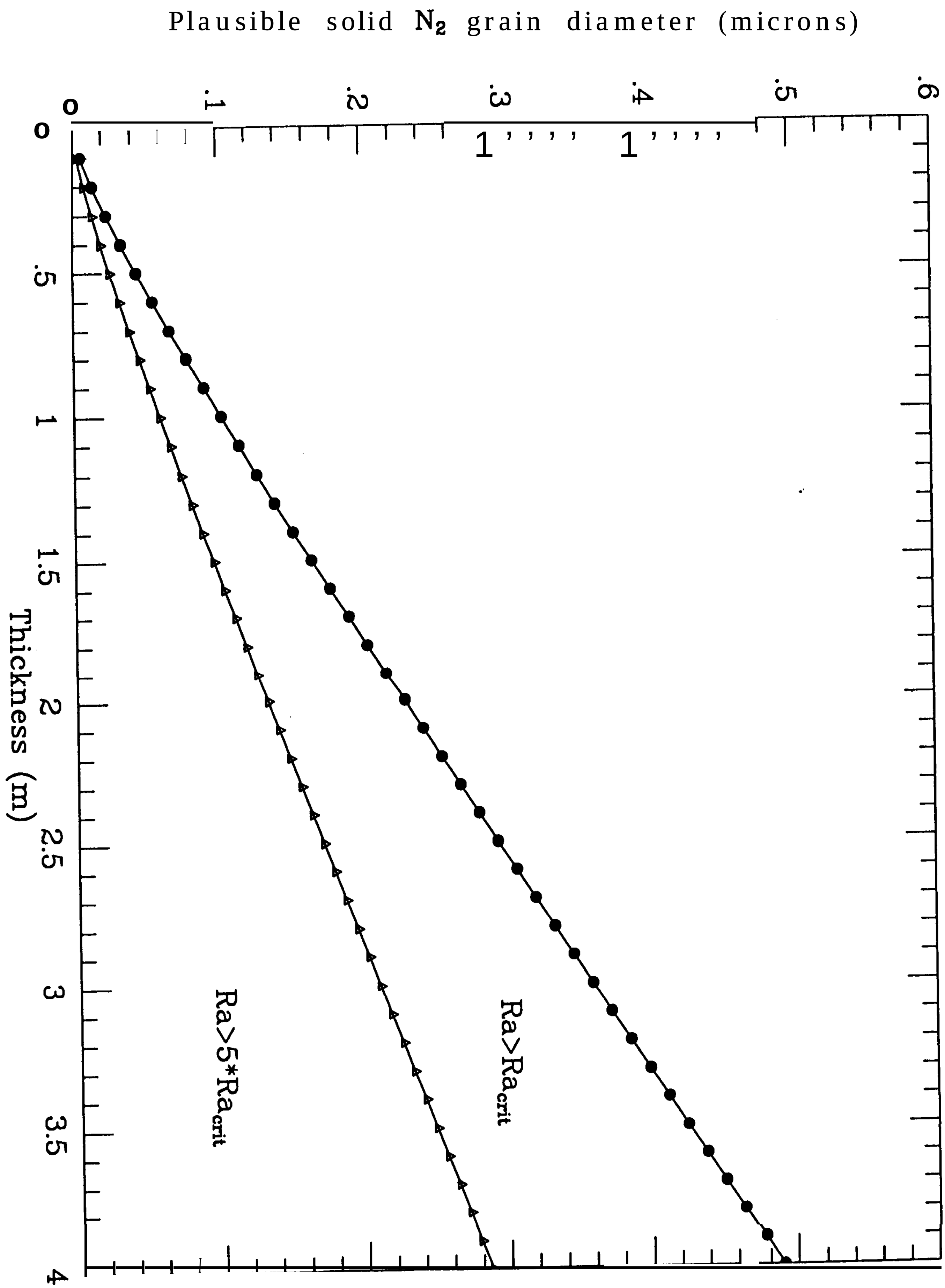
Fig. 4. Nitrogen grain diameters sufficiently small for thermal convection to start (the curve marked by filled circles) in a seasonal layer with the solid-state greenhouse effect. The "super" solid-state greenhouse effect is assumed with an intermediate value of 1 K/m for the conductive gradient (the dark underlayer having an albedo > 5%). The curve marked by open triangles shows N_2 grain diameters sufficient to obtain $Ra = 5 * Ra_{critical}$.



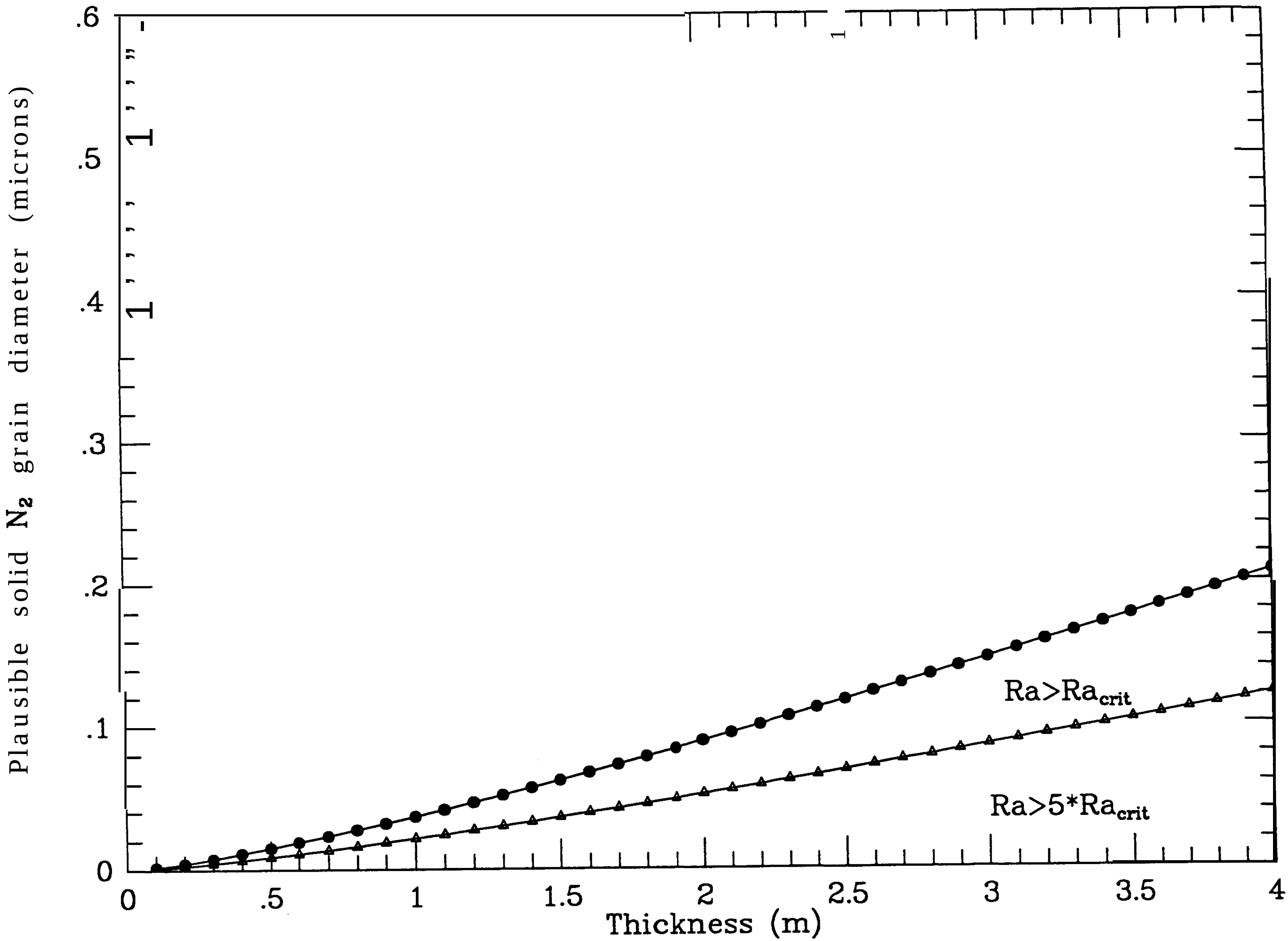
Duxbury et al. Fig 1



Duxbury et al Fig 2



Duxbury et al Fig 3



Duxbury et al Fig 4